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Heat Transfer with Very High Free-Stream Turbulence and Streamwise Vortices *

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Results are presented for two experimental programs related to augmentation of heat transfer by complex flow characteristics. In one program, high free stream turbulence (up to 63%) has been shown to increase the Stanton number by more than a factor of 5, compared with the normally expected value based on x-Reynolds number. These experiments are being conducted in a free-jet facility, near the margins of the jet. To a limited extent, the mean velocity, turbulence intensity, and integral length scale can be separately varied. The results to date show that scale is a very important factor in determining the augmentation. Detailed studies of the turbulence structure are being carried out using an orthogonal triple hot-wire anemometer equipped with a fourth wire for measuring temperature. The v' component of turbulence appears to be distributed differently from u' or w'. In the second program, the velocity distributions and boundary layer thicknesses associated with a pair of counter-rotating, streamwise vortices have been measured. There is a region of considerably thinned boundary layer between the two vortices when they are of approximately the same strength. If one vortex is much stronger than the other, the weaker vortex may be lifted off the surface and absorbed into the stronger.

Foreword

Most heat transfer research is conducted in low-turbulence tunnels, that is, with less than 0.5% turbulence, in flows especially refined to be spanwise uniform and steady. These conditions produce a "low-limit" estimate of heat transfer for a given mean flow and geometry. Free stream turbulence, or unsteadiness, or streamwise vortices increase heat transfer.

Even a small amount of free stream turbulence will advance the transition upstream, exposing more surface to turbulent heat transfer.

Free stream turbulence of 4 to 6% or larger may increase heat transfer even in fully turbulent regions [Blair, Ref. 1].

Streamwise vortices can thin the boundary layer, increasing heat transfer.

Most research studies of the turbulence effects use grids and let the turbulence relax until nearly homogeneous and isotropic before heat transfer studies are made [e.g. Blair, 1983].

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Gas turbines, on the other hand, run with turbulence up to 20-30%, which is probably highly anisotropic and well laced with large coherent structures coming downstream from the combustion chamber. Dils and Follansbee [Ref. 2] measured up to 16% in the discharge of a laboratory scale combustor in a bench test. They reported increases in heat transfer of over 50% on the stagnation line of a cylinder in that flow. Other recent experiences (Rohde, [Ref. 3]) suggest 20 to 30% as a reasonable value for the relative turbulence near a typical first turbine nozzle ring.

The flow through a gas turbine may not look much like the flow most researchers have in mind when they think of "turbulence." It is not difficult to imagine, superimposed on the "normal" turbulent fluctuation a whole family of flow disturbances whose spatial and temporal characteristics are determined by the engine configuration upstream of the point observation.

Among the phenomena which may be present (either intermittently or steadily) are:

(1) large scale, low frequency quasi-coherent structures,
(2) streamwise vortices,
(3) wakes from upstream vanes or blades,
(4) regions of high turbulent shear stress.

This paper describes recent results from two programs at Stanford, one concerning the effects on heat transfer of very high free-stream turbulence and the second concerning the effects of streamwise vortices.

The high turbulence has, so far, been created by placing the test plate in the margin of a large diameter free jet. This exposes the plate to a flow in which the local turbulence intensity can be as high as 70%. Putting the plate at different distances from the jet exit, and at different distances from the axis of the jet allows a certain degree of independence in choosing the mean velocity, turbulence intensity, and the integral length scale.

There is no assurance that this flow is like that which exists in a gas turbine, but it need not be the same to provide clear evidence that chaotic, unsteady, and highly Turbulent (with a capital T!) flows can result in heat transfer rates far higher than predicted by the usual correlations. One objective of this program is to demonstrate how high the "upper bound" of turbulent heat transfer can be pushed, at a given x-Reynolds number based on mean velocity. This will not prove where the upper bound is in a gas turbine, but will show at least where the lower limit of that upper limit might be. A second objective is to identify the turbulence descriptors which best relate to the increased heat transfer. This latter issue is critically important, since we must know what aspect of turbulence best correlates with the increase in heat transfer before we can specify the measurements which must be made.

It would be very helpful to have a "good" description of the flow field in an engine, to guide the present experiments, but such data are not available. In fact, the present work has already raised some troubling questions about the sufficiency of the usual set of turbulence measures. The issue is, "What aspect of a turbulent flow field best correlates with the increase in heat transfer?" There is no assurance that measures of the mean velocity, turbulence intensity, and integral length scale will suffice to identify the heat transfer aspects of a flow. In fact, the work reported at HOST last year already contained evidence that fixing these three parameters <u>did not</u> fix the heat transfer. Until we know what aspect of the flow to measure, we cannot even enter a sensible request for "Engine Data."

The second program reported here concerns streamwise vortices, and their effect on heat transfer to turbulent boundary layers. This issue has attracted much attention over the last several years, chiefly with regard to the end-wall heat transfer. Several different vortical structures have been identified by flow visualization, but characterization of their effect on heat transfer has been slow in coming. This report describes some of the hydrodynamic features of a streamwise vortex pair which might relate to their effect on heat transfer. These results are described in the section entitled Phase II -- The Effects of Streamwise Vortices.

Phase I: The Effects of High Turbulence

During the past year, effort on this project has been concentrated on expanding the range of variable covered in the free-jet facility, documenting the turbulence structure in the free-stream and in the boundary layers, and designing an internal flow facility to run in parallel with the free-jet facility. The results will be presented in that order: first, the heat transfer measurements, then the turbulence measurements, and lastly, the plans for the new facility.

Figure 1 is reproduced from the 1985 HOST report and shows a schematic of the free-jet facility used in these studies. The test plate is 0.60 m wide and 2.5 m long, divided into 8 test plates, each 0.3 m long. Each test plate is of 1 cm thick Aluminum, equipped with 5 thermocouples in a cross-pattern, and a single-panel electric heater which covers the entire back face of the plate. The back face is protected with 6 cm of Fiberglass insulation, to minimize heat loss.

The test plate was checked for repeatability and baseline values by installing it in a closed-loop, low turbulence heat transfer tunnel. Data from the test plate agreed with the accepted correlation for a constant wall temperature turbulent boundary layer within +/- 4%. The test plate was then installed twice into the free jet, at the same nominal position coordinates and flow conditions. The two sets of results agreed within better than +/- 2%. By these three tests, the credibility of the test plate as a heat transfer device was established, as well as the reproducibility of the data in the free jet. These results were presented at the 1985 HOST meeting.

Figure 2 is also reproduced from the 1985 HOST report, and shows the effects of free stream turbulence up to 48%. The envelope within which the Stanton number may lie is bounded on the bottom by the usual low-turbulence correlations for laminar and turbulent boundary layers. At 48% turbulence, the Stanton number lies above the usual correlation by about a factor of 4 and has a discernibly lower slope, in log coordinates.

During the past year, we have extended the turbulence level of the tests from 48% to 63%, with runs over a range of mean velocities from 0.5 to 5 m/sec, with integral length scales between 4 cm and 17 cm. A total of 60 different combinations have now been run.

Results of the high turbulence heat transfer taken to date are summarized in Figure 3, in coordinates of St/Sto vs. Re_x. Each line of symbols represents one run. The points are measurements on the individual plates. St/Sto is the ratio of the Stanton number with high turbulence to the Stanton number which would have existed at the same mean-flow x-Reynolds number, but with no turbulence. On any one line of data, or comparing any two lines having the same mean velocity, this ratio is a direct measure of the heat transfer augmentation caused by the free-stream turbulence. It is not so direct to compare two line of different mean velocity.

The results shown cover the entire range of test conditions: various combinations of free stream velocity (.47 to 2.89 m/s), Tu (22% to 63%) and integral length scale (4-17 cm).

It is apparent, from Figure 3, that the effects of turbulence are not simple to correlate: No simple proposal orders the data. For example, turbulence intensity alone does not explain the comparison between Runs 1 and 3 (numbering down from the top of the figure): those two runs have approximately the same turbulence intensity, but the augmentaion is far higher for the low velocity than the high. Also, examining Runs 2 and 3, we see two runs at about the same mean velocity (0.87 compared with 0.89), and about the same integral length scales (9.0 and 10.0 cm), but significantly different turbulence intensities (48% and 63%), yet the two flow conditions produce almost exactly the same heat transfer augmentation: about 3/1. This same "insensitivity" is displayed by Runs 4 and 5, which differ by 10% in their turbulence intensities, but hardly at all in their heat transfer responses.

Several One-Parameter suggestions have appeared in the literature in the past 10 years, usually expressing the heat transfer augmentation in terms of turbulence intensity. Based on the present results, it appears that these cannot succeed, at least for the highly disturbed flow we are dealing with here. A broader treatment is required.

A stepwise multiple linear regression program was used on the present data set, a program which sought the most significant parameter from a list of candidates provided, and extracted its effect before seeking the next most important parameter. The coefficients were not forced, not was the order of parameter selection.

The program generated the following relationship:

$$St^{*} = 0.440 = \frac{St}{Re_{\chi}^{-0.395}\left(\frac{\lambda}{\chi}\right)^{-0.204}\left(1-\frac{y}{x_1}\right)^{-0.43}}$$

The correlation coeffient, R^2, for this relationahip was 0.95.

In this relationship λ is the integral length scale, y is the distance from the test plate to the centerline of the jet (at the leading edge), and x_1 is the distance from the leading edge of the test plate to the nozzle exit plane.

Of the 420 data points recorded, none lie more than 18% from that line, or more than 20% from a simpler, perhaps more physically satifying form:

$$St^{**} = 0.405 = \frac{St}{\left[Re_x\left(1-\frac{y}{x_1}\right)\right]^{-0.2}\left[Re_\lambda\left(1-\frac{y}{x_1}\right)\right]^{-0.2}}$$

Such results are useful, but dangerous if misinterpreted or misapplied. Any correlation arrived at by such a purely formal means must be viewed with caution, and its limitations kept in mind. It is not a predictor of expected results for tests outside the present operating envelope. It may not even be a good interpolator by which to predict the results of new tests whose conditions lie within the envelope, but which involve new combinations of the variables, combinations not included in the data base. It is a correlation which describes the existing data, and nothing more: 420 data points taken from 60 runs, each with 7 data points, for the

combinations of conditions we have run. We plan to investigate the robustness of these correlations by testing their predictions against a set of runs not included in the present correlation-generating base, but these tests have not yet been done. We hope these correlations will lead us to something more physically based.

Note that turbulence intensity does not appear in either of these correlations. If forced in, Tu appears with an exponent of +0.03: a very nearly insignificant effect. If only Re and Tu are offered as candidates, but not λ, the resulting correlation has a much lower value of R^2.

The high value of R^2 suggests that all of the significant variables are included, somehow, in this correlation. A constant value of the "position" parameter (1 - y/x) must surely correspond to some invariant combination of the hydrodynamic parameters of the free jet. We haven't found what those are, yet, but we are working on identifying them.

In parallel with these heat transfer tests, detailed hydrodynamic studies have been made of the turbulence distributions within the boundary layer, by hot-wire anemometry. Previous hot-wire results reported from this project have come from a single wire, parallel to the test surface. This simple system was used to characterize the free stream turbulence, for the purpose of ordering the heat transfer data sets. For the detailed studies within the boundary layer, a more sophisticated system was introduced. An orthogonal triple-wire probe was used for the boundary layer studies, with real-time analog processing of the linearized signals from the three individual wires yielding real time, instantaneous U, V, and W velocity components in laboratory coordinates. The system has been used (and reported) before [Ref. 4]. It produces both time averaged and instantaneous values of U, V, W, u', v', w', u'v', u'w', and v'w', and products of these terms. A fourth wire, for temperature measurement, has been added under this project. The temperature signal is used in a fourth channel of analog processing which is connected to the velocity circuitry so as to compensate the instantaneous velocity signals for the instantaneous temperature, as well as to display the temperature fluctuation, t'. Thus, turbulence data can be taken in a heated boundary layer, without contamination of the velocity signals from the temperature fluctuations. In addition, the turbulent heat flux, v't' can be directly measured. We have not yet completed the qualification tests of the direct measurement of v't', but the preliminary results were good..

Figures 4, 5, and 6 show typical distribution of the mean velocity, the turbulence components (u' , v' , w' , and q), and the turbulent transport of momentum, -u'v'.

The mean velocity distribution is plotted against the y-position normalized on the momentum thickness of the boundary layer. The present results are compared with a seventh-power profile, for illustrative purposes. The present data are more sharply "squared off" than the usual turbulent boundary layer--indicative of higher shear stress (and heat transfer) at the wall. The distributions of q^2, $\overline{u'^2}$, and $\overline{w'^2}$ are similar in shape, rising exponentially from zero to the free stream value. The $\overline{v'^2}$ distribution is qualitatively different from the others.

The distributions of turbulent heat flux and shear stress are similar in shape and both indicate the existence of a very thin layer near the wall, wherein the shear strees and heat flux are constant. The quad-wire probe is too large to get data very close to the wall: those studies will have to be done with more conventional probes.

We are continuing the quad-wire study, and intend to document the structure of these layers for each of the conditions which has a significantly different effect on heat transfer and try to identify which aspect of turbulence is most closely associated with high augmenatation of heat transfer.

For the next year, we will move a part of the effort into a closed loop tunnel, generating high turbulence using a combustion chamber simulator. The objective, once again, will be to first identify flows with very aggressive turbulence characteristics, judged by their effect on heat transfer, and then to measure those characteristics. The combustion chamber simulator will be a rectangular box with replaceable sides, closed at the upstream end. It will be installed at the upstream end of the test section, extending upstream into the present nozzle. All 5 faces (4 sides and the upstream end) will have replaceable panels. Holes of different diameters will be used to adjust the larger scales of turbulence. Similar patterns of holes will be used for all sizes. A bypass gate will allow the test section mean velocity to be reduced, at constant turbulence kinetic energy. Prototype tests have show significant enhancements of heat transfer near the leading edges of flat plates in such a flow, but no detailed data have been taken.

From a comparison of the free jet and the internal flow results we hope to be able to identify which aspects of turbulence are responsible for the large increases in h and, perhaps, how to manage them by hardware design.

Phase II -- The Effects of Longitudinal Vortices

The objective of the second phase of the work is to examine the heat transfer effects of longitudinal vortices embedded in otherwise two-dimensional turbulent boundary layers. This simple case is meant to model the effects of embedded vortices which can be introduced by fixed support struts, cooling air jets, and transverse or longitudinal curvature. The experimentation couples spatially resolved heat transfer measurements with detailed mean velocity and turbulence measurements.

Earlier work, under separate funding examined the effect of single vortices of moderate strength [see Eibeck and Eaton, refs. 3 and 4]. The single vortex was found to produce substantial local augmentations of the heat transfer coefficient in the downwash region of the vortex. Fluid dynamics measurements showed that the effect of the vortex was simply to locally change the boundary layer thickness. Structural changes in the inner part of the boundary layer were minimal.

The work is presently being extended to pairs of vortices which are a common occurence in practical situations. The experiments are conducted in a two-dimensional, boundary-layer wind tunnel with a freestream velocity of 16 m/s and typical momentum-thickness Reynolds numbers of about 2000. The heat transfer coefficient is measured on a constant-heat-flux surface using 160 thermocouples to obtain good spatial resolution. All three mean velocity components and all components of the Reynolds stress tensor are measured using miniature five-hole probes and cross-wire anemometers. Counter-rotating vortex pairs are generated using pairs of half- delta-wing vortex generators which protrude from the wall.

To date, we have completed the acquisition of mean velocity and skin friction data for 12 different vortex configurations. Typical data are shown in Figure A. The striking feature is the broad region of boundary layer thinning and augmented skin friction between the two vortices. Clearly, this vortex pair would cause a very large increase in the average skin friction and heat transfer coefficients. Cases for which the common flow between the vortices is directed away from the wall have a

different behavior; the vortices propel each other out of the boundary layer and the effect on the heat transfer coefficient is minimal. One case involved a pair of vortices with unequal strengths, a rough model for the vortices on a turbine endwall. The vortices were swept towards each other by their image vortices, then the weaker vortex began to lift above the stronger. After a short distance, the weaker vortex lost its identity as it was absorbed into the stronger vortex.decreased on the other.

We are presently acquiring full planes of Reynolds stress data for two representative cases. Following that, heat transfer data will be obtained for all fifteen cases.

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FIGURE CAPTIONS

Fig. 1. Schematic of the free jet facility.

Fig. 2. High turbulence effects on heat transfer

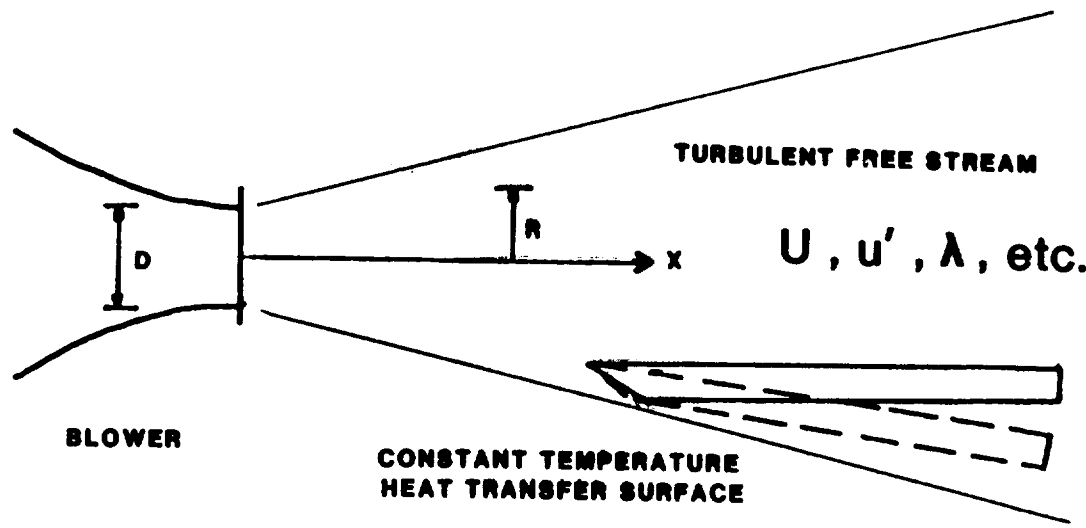
Fig. 3. Summary of high turbulence heat transfer results.

Fig. 4. Representative profile of the mean streamwise velocity, U.

Fig. 5. Representative distributions of turbulence.

Fig. 6. Representative distribution of turbulent shear stress.

Fig. 7. Effects of a typical embedded vortex pair on mean velocity and skin friction.



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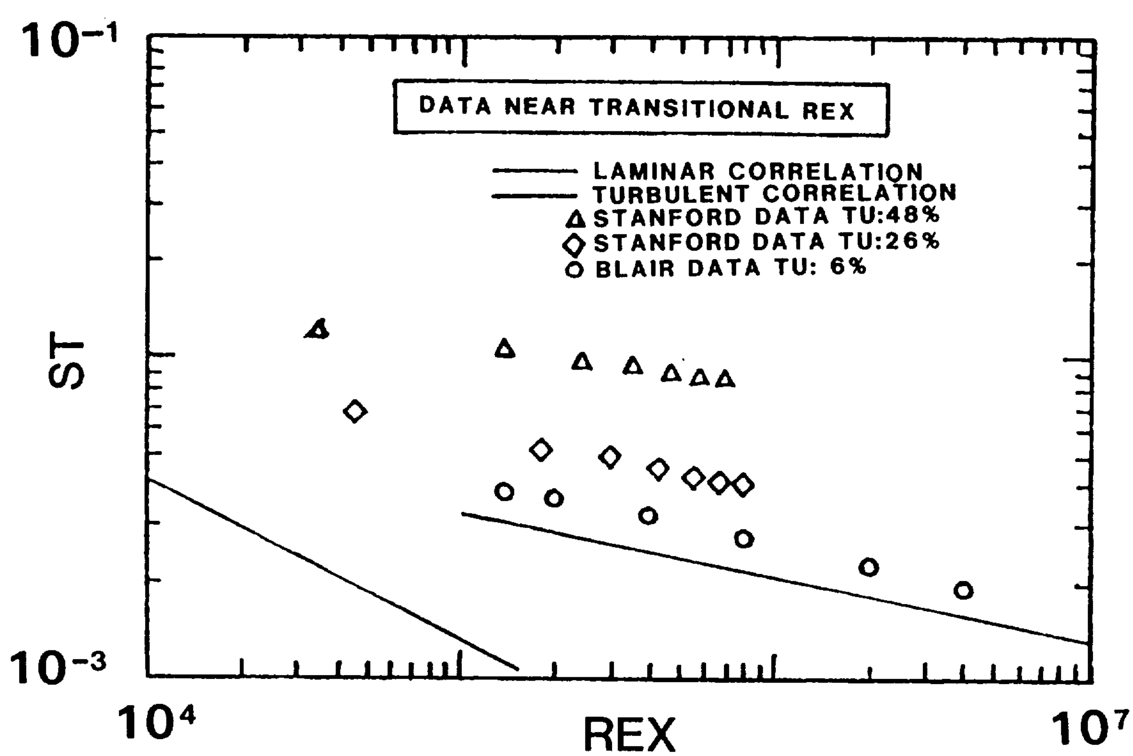
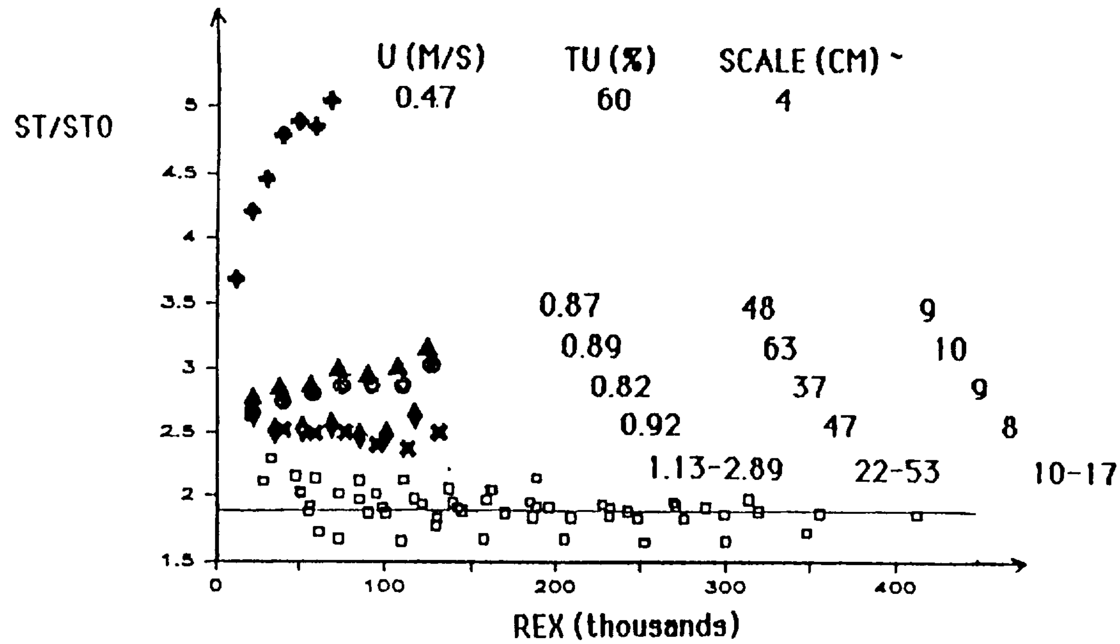


Fig. 2. High turbulence effects on heat transfer



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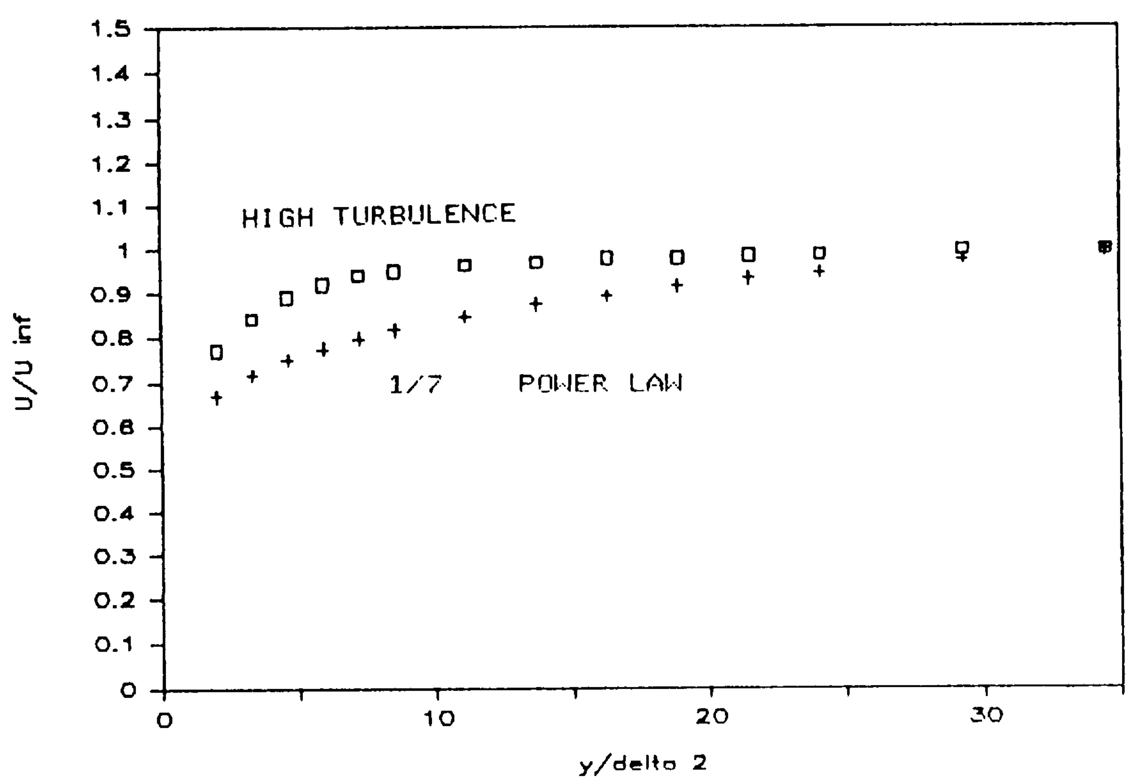


Fig. 4. Representative profile of the mean streamwise velocity, U.

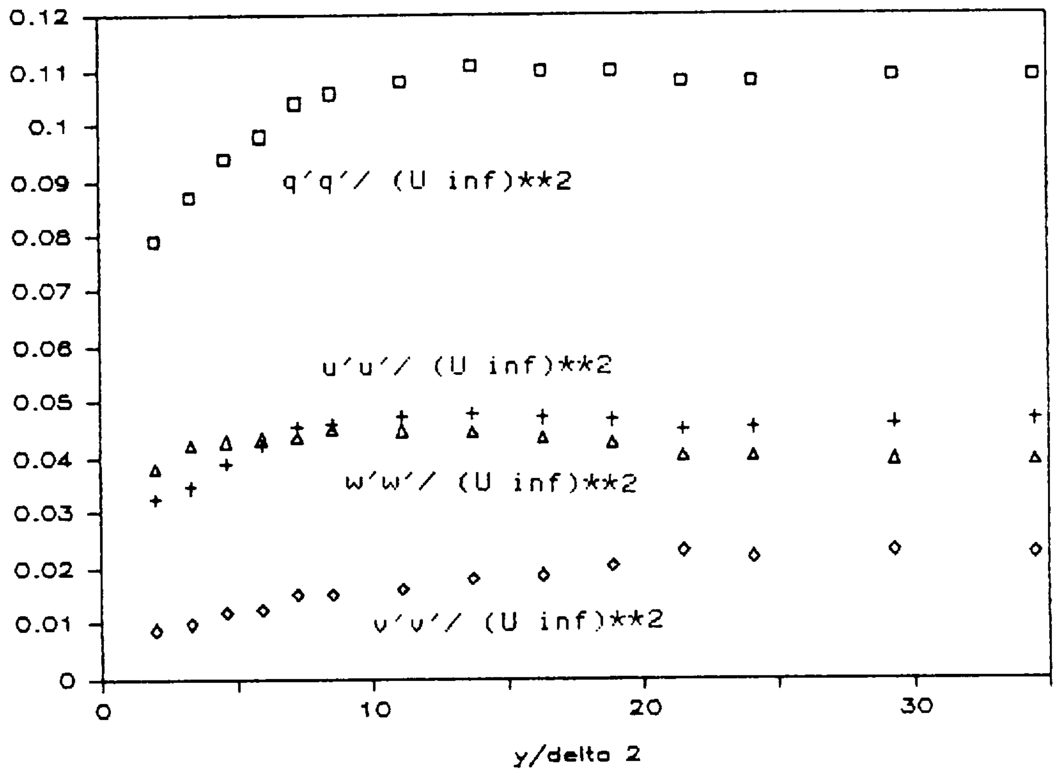


Fig. 5. Representative distributions of turbulence.

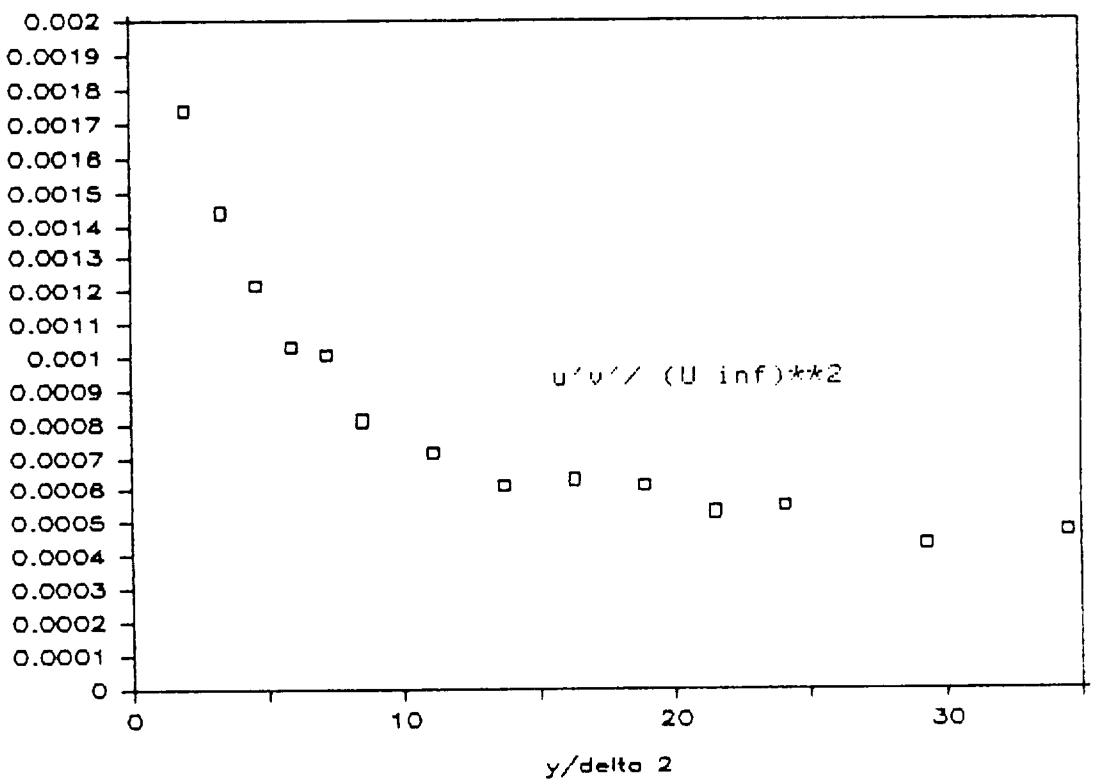
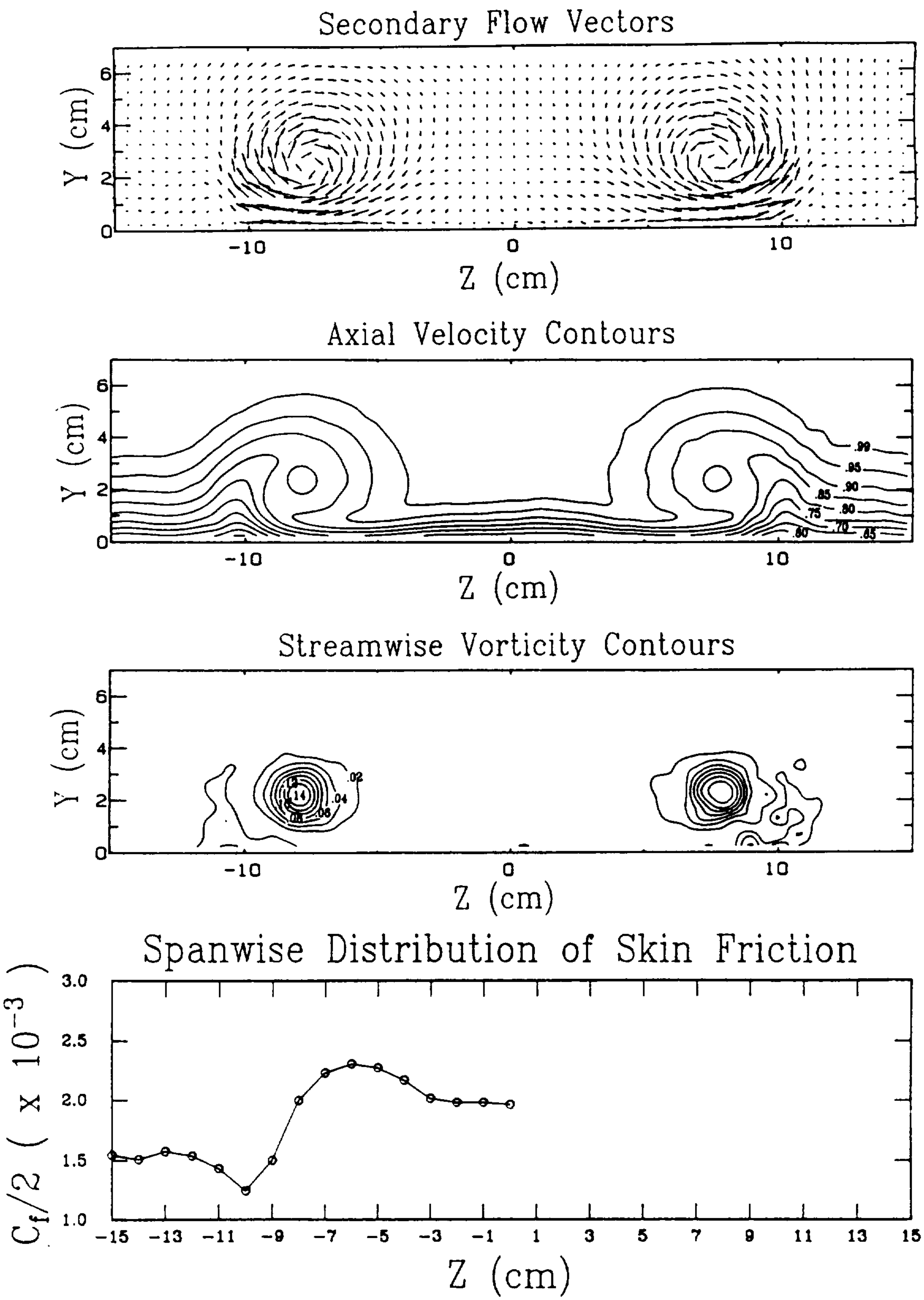


Fig. 6. Representative distribution of turbulent shear stress.



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